Underwater Glider Networks for Adaptive Ocean Sampling

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LONG-TERM GOALS

The long-term goal of this research is to enable a cooperating group of underwater gliders to perform efficiently and robustly as an autonomous, adaptive sampling network in a three-dimensional, dynamic ocean environment. This will involve developing the mathematical infrastructure and design tools for effecting feedback-controlled, schooling-like network behavior in an unsteady flow field while exploiting the natural dynamics of the ocean.

OBJECTIVES

We are interested in developing the mathematical framework and the integrated design methodology for coordinating a glider network to provide improved sampling efficiency and efficacy using ocean model prediction data, observations and Lagrangian structure computations. The fleet of gliders serves as a mobile and re-configurable sensor network for investigating the ocean. Our technical objectives include the following:

1. To develop glider network control strategies that exhibit “emergent intelligence” at the group level using simple control laws at the individual level, much like schools of fish. Group-level behaviors may include the ability to maneuver in a particular formation, adjust the group shape, size, orientation and density in response to measured (or predicted) data in real time, climb gradients and track and map features.

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14. ABSTRACT
The long-term goal of this research is to enable a cooperating group of underwater gliders to perform efficiently and robustly as an autonomous, adaptive sampling network in a three-dimensional, dynamic ocean environment. This will involve developing the mathematical infrastructure and design tools for effecting feedback-controlled, schooling-like network behavior in an unsteady flow field while exploiting the natural dynamics of the ocean.

15. SUBJECT TERMS

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2. To investigate using the method of controlled Lagrangians as a framework in which network control strategies can be derived from artificial potentials and gyroscopic forces and can be integrated with a graph theoretic setting for describing a time-varying communication topology.

3. To investigate the use of dynamical system theory tools and software for computing Lagrangian structures to understand the dynamics and control of underwater gliders in a three-dimensional ocean environment.

4. To extend the glider network control strategies so that they not only perform successfully in spite of a dynamic ocean environment but also perform well because they exploit knowledge of the dynamics of the sea and the consequential tendencies of the gliders to move easily in certain directions. In particular, the objective is to integrate the network control strategies with the computation and analysis of Lagrangian structures.

5. To develop variational integrators for the simulation of one or more underwater vehicles and investigate the interaction of vehicles and also the interaction with vortex structures.

6. To apply these technologies to adaptive sampling in the AOSN-II Monterey Bay Field Experiment in the summer of 2003. This will involve integration with ocean model predictive capabilities and practical glider operating conditions.

APPROACH

The approach and methodologies employed, corresponding to the above objectives, are as follows:

1. We build on the technique of adaptive gradient climbing and maneuvering (see Leonard and Fiorelli [2001], Ogren, Fiorelli and Leonard [2002], Bachmayer and Leonard [2002]), whereby the group, serving as a re-configurable sensor array, uses its local information and virtual leaders to locate interesting regions and to adapt accordingly. The vehicles respond according to feedback control laws derived from artificial potentials and stay near virtual bodies that are driven by measurements of the environment, for example, gradient measurements. We also consider a model in which the individuals move at a constant speed and the control law determines the steering. The approach in this effort involves making use of results from the literature on coupled oscillators.

2. The use of controlled Lagrangians has already been successful in the control of single systems (see, for example, Chang et al. [2002]). We develop this theory in a network context (with the individual systems connected by sensor and information flow) and plan ultimately to merge it with the other techniques for a glider network, as in item 1. This effort requires models for gliders, such as those developed by Leonard and Graver [2001].

3. Much progress has been made, using the software MANGEN, on the problem of understanding flow structures in Monterey Bay and other ocean and coastal environments. In this work we use flow field data, either as measured by HF Radar or as computed by ocean models, to compute Lagrangian coherent structures (LCS). The approach allows for an interpretation of the observations or model output that will be important for directing gliders.

4. We merge the LCS computations with glider dynamics so that we can determine the effect of the dynamics on the vehicles and how to respond appropriately. One strategy is to navigate, using

groups of vehicles moving together in a coordinated way as a result of potential and gyroscopic control strategies, along *navigation channels* (that is, stable manifolds, or more precisely, repelling material lines) in the sense of the finite-time, computational theory (see, for instance, Haller and Yuan [2002]) in order to reach the *front surfaces* (that is, unstable manifolds, or more precisely, attracting material lines). George Haller of MIT is a consultant and collaborator.

5. We plan to use existing variational methodologies, such as those in Rowley and Marsden [2002] and references therein as simulation tools; these methods show superior performance in terms of energy behavior, especially for long-time or complex simulations (see, for instance, Lew et al [2002]). We aim to also make use of known variational structures in fluid mechanics, especially those involving the interaction of solids and fluids (e.g., Leonard and Marsden [1997]) and the interaction of vortex structures and solids (e.g., Shashikanth et al [2002]).

6. To contribute to the adaptive ocean sampling experiment in Monterey Bay in the summer of 2003, we integrate our methods with the tools of the collaborating research teams so that we can demonstrate some of the versatility and capability of an underwater glider fleet serving as a sensor network. The output from the ocean models, namely the predicted data and the determination of areas of greatest model uncertainty and scientific interest, together with the interpretations from the experimental oceanographers and the ecologists provides the input to our glider network motion planning and feedback control strategy. Feeding back model prediction data and observational data, the strategy addresses both the problem of getting the glider network to the features/sites of interest and the problem of guiding the glider network so that it most effectively samples the features/sites of interest once it is there. We have collaborated with a number of teams. We have worked with A. Robinson and P. Lermusiaux at Harvard and I. Shulman at NRL to link the HOPS and ICON models with control strategies. We have collaborated with the experimental team of Dave Fratantoni at WHOI to implement control laws on the underwater vehicles, first in the Bahamas and then in Monterey Bay. Simulation development is an important tool for testing various control strategies we have developed, including gradient climbing and virtual body methods, and also to test the effect of the currents using the MANGEN software which identifies coherent Lagrangian structures. Adaptation of our strategies to the realities of the hardware and software constraints in the Monterey Bay experiment is an important step.

The effort is led by N. Leonard (PI) with the Caltech contribution led by J. Marsden (co-PI). C. Rowley (co-PI) focuses on low-dimensional modeling of fluids and R. Bachmayer (research staff at Princeton) focuses on simulation and implementation issues. Graduate students E. Fiorelli and P. Bhatta (Princeton) and S. Shadden (Caltech) focus on the coordinated control strategies and the integration with Lagrangian structure computations. C. Coulliette (post-doc at Caltech) and Francois Lekien (graduate student at Caltech) focus on computing and exploiting Lagrangian structures from flow data.

WORK COMPLETED

Within the method of virtual bodies and artificial potentials (VBAP), we have addressed the problem of optimal mobile network configuration for minimizing error in the gradient estimate of a measured field. We have also proven convergence of the mobile network under these conditions to local minima or maxima of the field of interest. Using the method of controlled Lagrangians, we have developed control strategies for networked vehicles with unstable dynamics. We have also developed control strategies for coordination and obstacle avoidance using gyroscopic forcing as well as potential

shaping. This work makes use of the concepts of a detection shell and a safety shell and shows, in an appropriate context, that collisions are avoided, while at the same time guaranteeing that control objectives determined by a potential function are met. In a somewhat similar vein, we have developed steering control strategies and global convergence results for a group of vehicles with constant speed (motivated in part by the fixed average speed (relative to water) of the gliders during AOSN-II). This work relies on results from the literature on coupled oscillators. Additionally, implicit Lagrangian systems (ILS) have been defined and some of their basic properties developed. It is expected that this theory will be useful in the future development of networks of underwater vehicles.

Lagrangian coherent structure (LCS) computations were performed on historical ocean model data from Monterey Bay to test conjectures about the relationship between Lagrangian coherent structures and fronts and to test our strategies for using LCS for glider navigation. Additionally, a new computational technique was developed for computing key dynamical features, including almost invariant sets, resonance regions as well as transport rates and bottlenecks between regions in dynamical systems.

A multi-scale, adaptive sampling plan for AOSN was developed that integrates adaptive sampling techniques based on ocean model output and LCS and adaptive sampling from “real-time” feedback control.

The VBAP method for coordination and cooperation of a mobile sensor fleet was adapted for the constraints and operating conditions of the glider network used in Monterey Bay ’03. For example, restrictions on communication capabilities, asynchronous glide surfacings, latency, external currents and other constraints were accommodated. A simulator was created and used in Ocean Sampling Simulation Experiments (OSSE’s) with Igor Shulman from NRL who runs the ICON code. For example, we experimented with gradient climbing using aircraft SST data and ICON model output from August 2000 in Monterey Bay.

An experimental plan was developed and carried out as part of the Monterey Bay ’03 Field Experiment. We participated in the experiment from mid-July to early September 2003. Multi-glider coordination experiments were run, gradients were estimated, gliders were coordinated with other assets, gliders were used to track drifters and LCS was run on ocean model output.

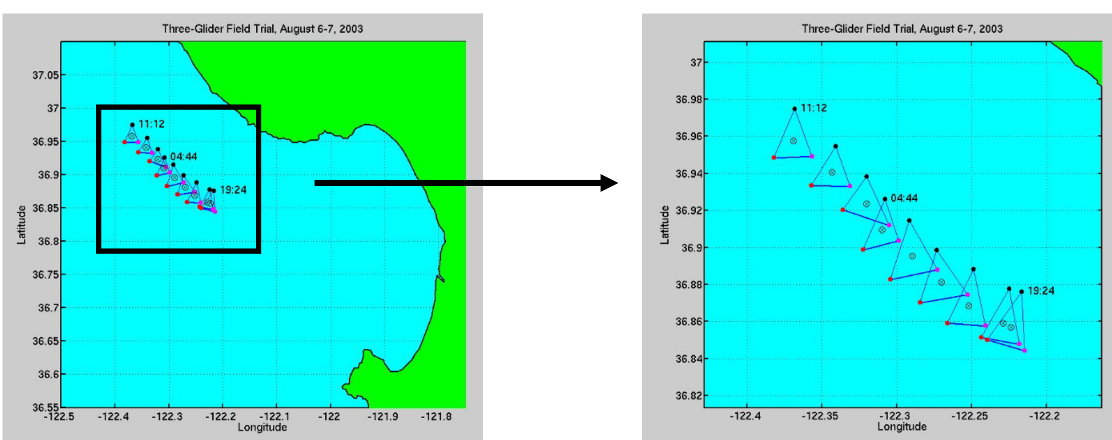

Figure 1: Monterey Bay ’03 experimental results: coordination of three gliders.

RESULTS

1. Using the VBAP methodology which involves "real-time" feedback (every two hours), a fleet of gliders can be coordinated to move in a formation. This formation can be rigid or can vary, e.g., can rotate, expand or contract. This can be done in the presence of significant currents. (See Figure 1 for results from Monterey Bay 2003).

2. Preliminary results show that a network of three gliders has the potential to provide meaningful, real-time estimates of gradients in measured (planar) fields such as temperature. Using our method such estimates can then be used as a tool for real-time guidance of the fleet to regions of interest.

3. We have provided an additional capability for a glider (or ultimately a glider group) to follow in real-time a drifter. This makes for the possibility of a Lagrangian mobile sensor network that would move in such a way to collect useful data along the path of a drifter.

4. Motion of gliders along an LCS takes better advantage of the local currents than does a glider that steers independently of a nearby LCS.

5. An examination of some MANGEN two-dimensional simulations based on HF Radar Data suggests that stable material lines correspond to temperature fronts in Monterey Bay. Figure 2 shows the superposition of a Lagrangian structure computed from HF Radar data on an ICON sea surface temperature (SST) field from August 2000. Furthermore, during the AOSN Monterey Bay Field Experiment '03, the measured path of a real drifter showed remarkable coincidence with an LCS computed from the flow field generated by the HOPS ocean model.

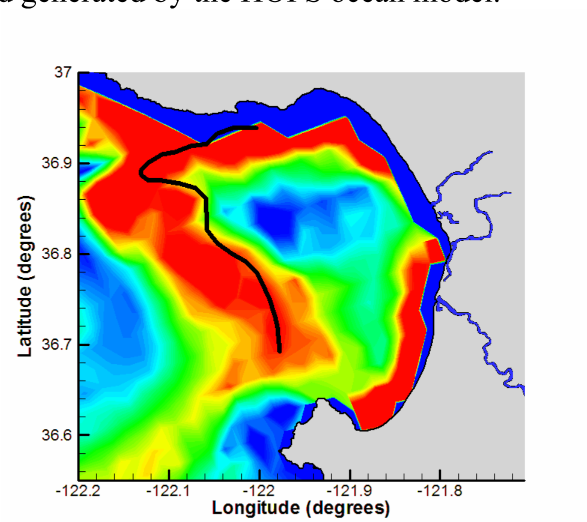

Figure 2: Superposition of Lagrangian structure computed from HF Radar data on ICON sea surface temperature (SST) field indicates coincidence of Lagrangian structures with fronts.

IMPACT/APPLICATIONS

The infrastructure we are developing will lead to the understanding of and design of specific control strategies for underwater glider networks in a dynamic ocean environment. This impacts not only the gathering of data for the adaptive ocean sampling experiment to be performed next summer in

Monterey Bay, but most importantly the longer term plans for finding and tracking features of interest and gathering data all in a systematic and sustainable way in various regions of Earth's oceans.

RELATED PROJECTS

Leonard participates in an NSF/KDI funded project joint with A.S. Morse (Yale), P. Belhumeur (Columbia), R. Brockett (Harvard), D. Grunbaum and J. Parrish (U. Washington) on coordination of natural and man-made groups. Schooling of fish and "schooling" of autonomous underwater vehicles are studied. A multiple-vehicle experimental test-bed is being developed at Princeton. See http://graham.princeton.edu/~auvlab/ and http://www.eng.yale.edu/grouper/

Leonard participates in an AFOSR funded project on Coordinated Control of Groups of Vehicles. This is a joint project with V. Kumar and J. Ostrowski at University of Pennsylvania. A focus of the project is understanding cooperation in the context of coordinated control of distributed, autonomous agents, and the collection and fusion of the sensor information that they retrieve.

Leonard and Marsden work on control and stabilization of mechanical systems, including autonomous underwater vehicles with internal actuation (e.g., internal rotors) using the method of controlled Lagrangians. This is a joint project with A.M. Bloch (U. Michigan), D.E. Chang (UCSB) and C.Woolsey (Virginia Tech).

Marsden is involved in an NSF/ITR project at Caltech on *Multiscale modeling and simulation* that aims to improve both the mathematical models and the simulation of multiscale phenomena, including fluid dynamical simulations and the variational integrator methodology. That project will interact with the present one in the simulation and modeling aspects of the problem.

Marsden is also working with Chad Couliette (who is the PI) on the ONR project *Lagrangian Analysis and Forecasting in the Oceans and Coastal Zones*. This project uses dynamical systems techniques to develop a detailed understanding of transport and mixing in the oceans and coastal zones. Ultimately, the program will lead to Lagrangian forecasting—the ability to make specific deterministic predictions about the advection and diffusion of passive scalars in the ocean. That project developed the software MANGEN which will be quite useful in the context of the current proposal. The project also developed the Open-boundary Modal Analysis (OMA) which is a substantial improvement on current techniques for data interpolation (to avoid dead zones, for example). These techniques may be quite useful, especially in the long run, in the problem of incomplete data sets in, for example, Monterey Bay.

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HONORS/AWARDS/PRIZES

N.E. Leonard, Princeton University, Plenary lecture at the Society of Industrial and Applied Mathematics (SIAM)'s Conference on Applications of Dynamical Systems, May 2003.

C. Rowley, Princeton University, Howard B. Wentz Jr., Junior faculty award for excellence in teaching and scholarship, 2003.